Development of 3D Angle-Interlock Woven Preforms for Composites

D N Sandeep, B S Sugun
Centre for Societal Missions and Special Technologies,
CSIR- NAL, Bangalore, India
sandeepdn@nal.res.in

K V Kundan
Advanced Composite Division,
CSIR- NAL, Bangalore, India

S N Shwetha, Ashwathi and T Ananthakrishnan
Textile Technology Department,
Govt. SKSJT Institute, Bangalore, India

***Abstract*— The advent of three dimensional (3D) reinforcements has been mainly to overcome the issue of delamination and improve upon the damage tolerance properties by introducing fibres in the thickness direction for advanced composite applications. 3D preforms can be developed using various techniques. Angle-interlock weaving is one of them. This paper details about the efforts being put at CSIR-NAL for developing angle-interlock woven preforms. Four types of angle-interlock structures viz., layer-to-layer and through thickness (both with and without stuffer yarns) were developed using 6K, 400 Tex TC-33 grade Carbon tows on a custom designed handloom. The preforms without stuffer yarns had 4 layers of warp and were of 1.5± 0.2 mm thick. Preforms with stuffer yarns had 6 layers of warp (including 2 stuffer yarn layers) and were of 2.3±0.1 mm thick. Thermoset composites were prepared from these preforms using EPOLAM 2063 (an epoxy based resin system) by RTM process. The fibre weight fraction for these composites ranged from 0.53 to 0.58 and they were subjected to mechanical tests such as tensile, flexural and interlaminar shear strength. Test results showed improved response (in the warp direction) with respect to shear properties while the tensile and flexural properties were equivalent to that of the plain woven composites.**

Keywords*— *3D reinforcement; Angle-interlock weaving

Nomenclature and definitions:
Warp : Longitudinal yarns used during weaving for cloth formation
Weft : Transverse yarns used during weaving for cloth formation
Stuffer : Yarns which do not interlace and remain straight in the woven structure
Let-off : Letting off of warp yarns in an incremental manner required for weaving.
Shedding : Means of separation of warp yarns using suitable devices for insertion of weft yarns
Picking : Insertion of weft yarns using suitable device in the separated warp yarns
Beat-up : Pushing the just inserted weft to the cloth formation edge called fell using a suitable device called reed
Take-up : Winding of cloth onto cloth roller.
Reed : Comb like device used to push the just inserted weft to the cloth fell
Dobby : Shedding device responsible for selection of heald frames for shedding
Tow : Bunch of untwisted filaments
Tex : Designation for yarn count (weight in grams per 1000 mtr length of the yarn)
Interlacement pattern : The manner in which the warp and weft interweave
Weave design : comprises of design, drawing-in-order, lifting plan and denting order of requirement to the weaver to weave the structure on the loom
Thread/Yarn density : Yarn spacing per unit length of the fabric

I. INTRODUCTION

Composites in general comprise of 2D reinforcements made of Glass, Carbon and Kevlar bonded using suitable matrix/resin system. These composite materials find wide applications in areas of automobile, aerospace, space and defence. 2D reinforcements are mainly made of Uni-Directional (UD), Woven (Bi-Directional), Triaxial, Multiaxial, Knits, Braids and Random mats (chopped strands). Although these 2D reinforced composites are being used for several decades, their use in structural applications has been limited by some inferior mechanical properties[1] such as poor out-of-plane or through thickness properties, matrix dominated interlaminar shear stresses, delamination, etc., issues when compared with traditional aerospace and automotive materials (aluminium alloys and steel). In order to surmount many of these problems associated with 2D reinforced composites, 3D reinforced composites are being given considerable attention in recent years. 3D Reinforcement aims at providing continuous fibrous assemblies in all three directions (X, Y and Z directions), which are bound together by suitable means forming a cohesive structure. There are several ways of obtaining 3D reinforcements[1]. However, 3D reinforcements produced using the textile techniques of weaving, braiding, stitching and tufting are gaining most attention. Of the above textile techniques, one variant is 3D Angle-interlock weaving which has a very high potential for exploitation in developing 3D composites due to the advantage of it being producible on a 2D weaving machinery with some modifications. Added to the above advantage is the tailorability of the weave architecture, fibre contents in each direction and near net profile formation during the weaving of the 3D angle-interlock preform. This work details about the feasibility studies of development of 3D angle-interlock preforms on a handloom. The objectives were to understand the requirements needed to mechanise and also to get an indication about the composite properties that can be achieved.

II. 3D ANGLE-INTERLOCK STRUCTURES

3D Angle-interlock preforms comprises of laying up of several warp layers (longitudinal fibres – 'X' direction) one atop the other and interlacing them together with multiple wefts (transverse fibres – 'Y' axis) in predefined patterns (Fig 1) so as to form one thick preform with no identifiable individual layers. These thick preforms, when used in composites are expected to have improved shear, delamination resistance, impact damage tolerance and better heat distribution due to their interlaced constructions. These properties are required for structural applications (Eg: wing sections) as well as thermal applications[2] (Eg: exit nozzels, exhaust cones, brake pads etc.,).

Angle-interlock weaving is always carried out along the warp termed warp way. Here, warp way implies that the warp yarns traverses through the thickness of the preform and the weft path remains straight. 3D angle-interlock structures are represented by generating the weft cross-section diagrams. The wefts are arranged in a grid manner (depicted by dots) and the warps traverses around the several weft rows at an angle like a simple harmonic curve (depicted by lines). All the warp yarns travel in a similar fashion but most importantly would be parallel to each other. This in total ensures interlocking of the weft although individual interlacements do not happen as in the case of regular fabric constructions. These fabrics can be broadly categorized into two types based on the warp path in the structure, viz., through-thickness and layer-to-layer. The difference lies in the warp yarn path as shown in Fig 1a and 1b.

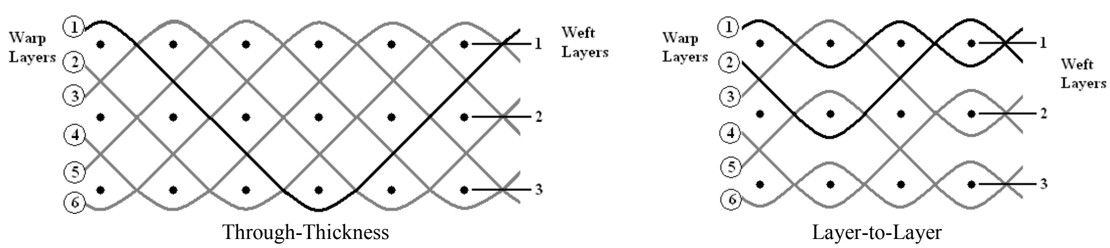
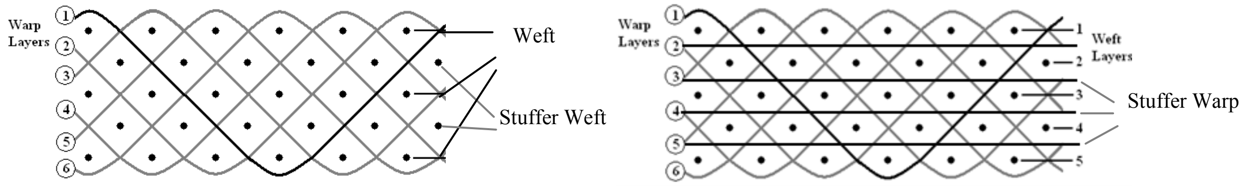


Fig 1: Schematic of a typical 3D Angle-interlock, a: Through-Thickness structure; b: Layer-to-Layer structure.

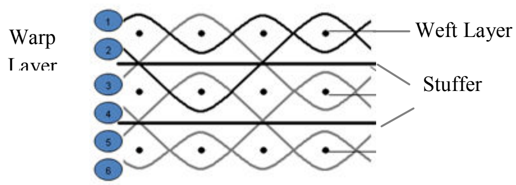
In the case of Through-Thickness structures each warp yarn travels throughout the thickness in a repetitive cycle binding all the layers together. This can be observed in the Fig 1a marked with a dark line. In the case of Layer-to-Layer structures each warp yarn travels upto an intermediary position and does not travel throughout the total thickness in a repetitive cycle. This can be observed in the Fig 1b marked with dark lines. Layer-to-layer structures are more versatile with several possible combinations of warp yarn paths binding two or more adjacent weft layers.

Further variations to a through-thickness structure can be done by the addition of stuffer yarns in warp direction. There is also the possibility of arranging the weft in offset manner, where-in, the alternate columns of weft would act as stuffer yarns (Fig 2). Stuffer yarns can also be introduced in the warp direction for layer-to-layer structures as shown in Fig 3. Once the structure is finalised and the warp paths are drawn, the weave design can be generated based on the standard conventional principles[3]. Weave design provides the required input for a weaver to weave 3D angle-interlock preforms.



Through-Thickness with only stuffer weft — Through-Thickness with stuffer warp and stuffer weft

Fig 2: Schematic of a typical 3D Angle-interlock, a: Through-Thickness structure with only stuffer weft; b: Through-Thickness structure with both stuffer warp and stuffer weft.



Layer-to-Layer with stuffer warp

Fig 3: Schematic of a typical 3D Angle-interlock Layer-to-Layer structure with stuffer warp.

III. EXPERIMENTAL WORK

Angle Interlock Woven Preform Development

Angle interlock preforms of four varieties were developed on a handloom (Fig 4) consisting of eight heald shafts. They were

- Layer-to-Layer with warp stuffer – LLWS
- Through-Thickness with warp stuffer – TTWS
- Layer-to -Layer without stuffer – LL
- Through-Thickness without stuffer – TT

For comparison purposes, a plain weave bi-directional (BD) fabric (with similar construction) was also woven on the same handloom (designated as 'P').

Carbon rovings of 400 Tex, 6K (6000 filaments of 7 micron each), TC-33 (aerospace grade) were used for the development. The reed count of 24's stockport was used which implies 24 dents for 2 inches or 12 dents per inch. The handloom used for preform weaving was equipped with custom designed multiple beam stand, eight heald frames for shedding and reed for beat-up along with other standard parts. All the operations such as shedding, picking, beat-up and warp tension adjustment by letting off and take-up were done manually.

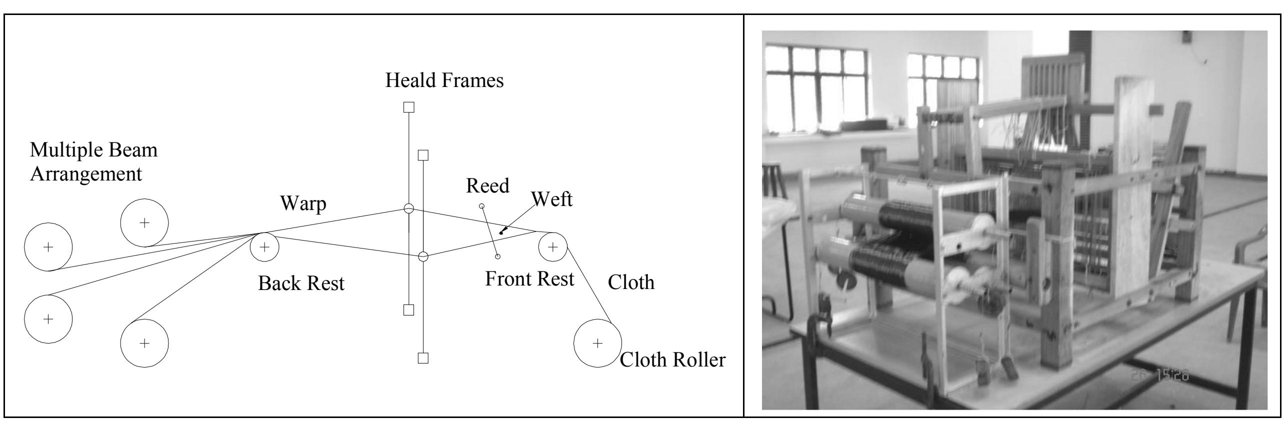


Fig 4: Line diagram Photograph of handloom used for weaving angle interlock structures

3D angle-interlock structures developed are shown in the following Fig 5.

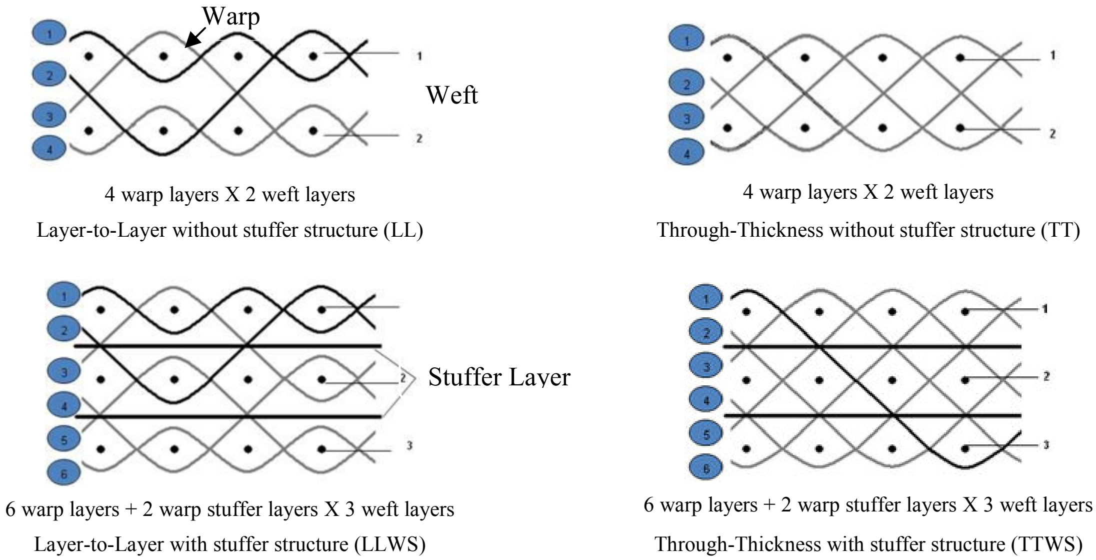


Fig 5: The 3D angle-interlock preform structures developed.

3D angle-interlock preform development involved the following steps.

1. Preform Thickness of about 2mm was arbitrarily fixed.
2. Number of warp and weft layers were determined based on the thickness of the preform.
3. Weft cross-section or the angle-interlock structure was generated based on the interlacing pattern (Layer-to-Layer or Through-Thickness).
4. Weave design consisting of design, drawing-in-order, lifting plan and denting order was generated based on the warp yarn path[4].
5. Warp preparation[5] comprised of warp distribution, beam preparation for let-off, leasing, drawing-in through the heald shafts as per the drawing-in-order and denting through the reed as per the denting order. Warp distribution carried out onto 4 beams based on the weave architecture and warp yarn path.
6. Weft winding was carried out on the handmade shuttle maintaining uniform tension.
7. Weaving was done pick by pick as per the lifting plan.
8. Take-up of the woven preform on the cloth roller was done in synchronisation with let-off.

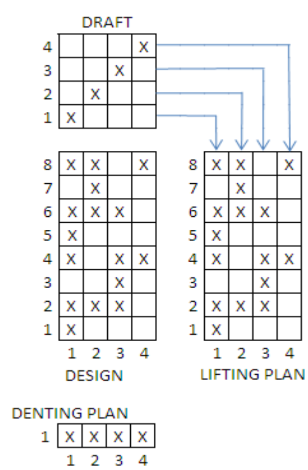


Fig 6 : Design, Draft and lifting plan for Layer-to-Layer angle-interlock structure.

Fig. 6 shows the typical weave design for a layer-to-layer angle-interlock structure required by the weaver to produce the preform. Here, Design indicates the interlacement pattern of warp and weft threads. The Draft indicates the manner of drawing the warp yarns through the heald eyes of the different heald frames. The Lifting plan denotes the order of lifting the heald frames to form sheds for pick insertion. The Denting plan indicates the order of arrangement of the ends in the reed.

Photograph of 3D angle-interlock woven preforms are shown in Fig 7. Woven preforms were analysed for their basic characteristics. Thickness of preforms without stuffer yarns were of 1.5± 0.2 mm and had areal weight of 1100±15 GSM. Thickness of preforms with stuffer yarns were of 2.3±0.1 mm and had areal weight of 1850±25 GSM.

Fig 7: Photograph of 3D Angle-interlock Woven Preforms

Owing to the handling difficulties of the carbon fibres which are brittle in nature and the weaving difficulties on a handloom, dimensions of the sample were restricted. Variation in thickness and GSM of preforms were attributed to difference in structure as well as them being woven on the handloom.

Fabrication of composites

The above preforms were used to prepare epoxy based composites by pressure assisted Resin Transfer Moulding process. EPOLAM 2063 resin system and MEGAJECT MVK RTM machine was used. Two flat mould plates with all-round clamping arrangement were utilised for this purpose. Depending on the thickness of the preform, suitable spacers were used. One of the mould plate consisted of one inlet port and one outlet port for aiding the resin transfer. The inner surface of the mould plates were applied with releasing agent before placing the preform. Spacers of required thickness were placed and moulds were closed with the help of sealant and mechanical fasteners. The prepared moulds were placed in the oven and preheated to 50-55°C. Resin and the hardener were mixed in the required proportions by the RTM machine and heated to 50-55°C. The outlet of the machine was connected to the mould inlet port and resin was pumped at constant pressure. Pumping was stopped when resin mixture started coming out of the outlet port on the mould. Mould was disconnected from the machine and placed inside the oven for curing at 80°C for 7 hours. The mould was cooled and unmoulded to take out the composite. The composite was trimmed and post cured at180°C for 4 hours.

In the case of plain woven fabric, 5 layers were stacked one over the other (about 2 mm thick) and composite was prepared adopting the same procedure.

The photographs of developed composites are shown in Fig 8. Composites made from preforms without stuffer yarns were about 1.5mm thick and had fibre volume fraction of 0.40 to 0.50. Composites made from preforms with stuffer yarns were about 2mm thick and had fibre volume fraction ranging from 0.45 to 0.49, which is equivalent to composite made from plain woven fabrics.

P	LL	TT	LLWS	TTWS

Fig 8: Photograph of Developed Composites

Mechanical Characterisation

Post cured composites were subjected to Flexural Strength, Inter Lamina Shear Strength (ILLS) and Tensile Strength tests in order to determine their mechanical characteristics as per ASTM test standards and values are tabulated in Table 1.

TABLE 1: DETAILS OF MECHANICAL PROPERTIES

Sl. No.	Preform Type	Inter Lamina Shear Strength in MPa		Flexural strength in MPa		Tensile strength (warp way) in MPa
1	P	46.92		650.94		426.28
		warp	weft	warp	weft	
2	LL	41.48	28.36	-	-	321.87
3	TT	40.1	24.15	-	-	290.1
4	LLWS	69.21	26.34	615.5	255.99	498.48
5	TTWS	71.57	28	685.73	289.36	520.1

In the case of LL and TT, flexural strength could not be carried out. Although variation exists in thickness, fibre volume fraction and fibre distribution in warp and weft direction, it can still be seen that, angle-interlock structures with stuffer yarns exhibit good all-round properties especially in the warp way. Structures without stuffer yarns showed no improvement when compared with layered composites. 3D angle-interlock (with stuffer) composites have shown characteristic improvement in the case of interlaminar shear strength, while flexural and tensile strengths remain more or less same as that of layered composites.

In spite of different weave architectures, the above test results clearly indicate improved mechanical properties for 3D angle-interlock (with stuffer) composites in comparison with plain woven (BD) laminated composites in the warp direction. Strength improvement can be attributed to the non-interlaced (no crimp as in BD fabrics) stuffer yarns in the warp direction. Fig 9 shows the plots for tensile strength and flexural strength of composites. Fig 10 shows the plots of ILSS of composites. It is evident from this work that 3D angle-interlock (with stuffer) structured composites posses 45-50% higher ILSS properties for the equivalent flexural and tensile properties in the warp direction. There also possibility exists for tailoring these properties (within set practical limitations) to meet the requirements of the end product in question by suitably playing with the yarn count and yarn density in that particular direction.

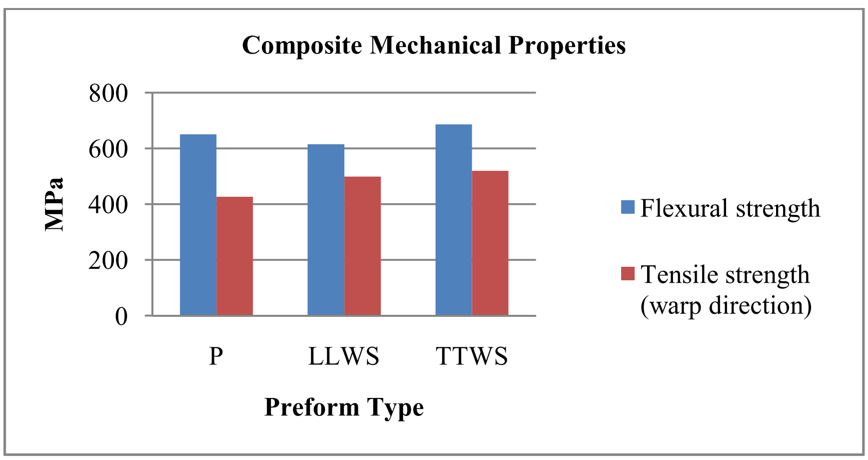


Fig 9: Plots for tensile strength and flexural strength of composites.

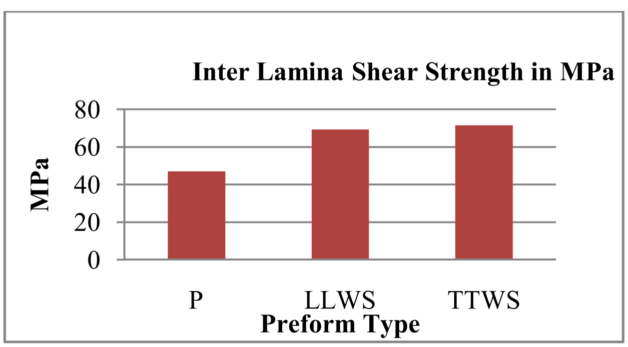


Fig 10: Plots of Inter Lamina Shear Strength of composites.

It should be noted that the values are only indicative but not conclusive as the development has been on a handloom which is susceptible to have variations in warp tension, weft density, beat-up force, take-up etc.,. Nevertheless, since all the preforms were developed on the same loom, the relative comparisons give a good indication of the potential of the3D angle-interlock composite technology. It should be noted that performance in any given direction is attributable to the textile weave architecture (yarn paths) which can be altered and designed (yarn spacing, count etc.,) to meet the specific requirement within some practical limits.

Mechanisation requirements for producing 3D angle-interlock preforms

One of the objectives of taking up this work had been to understand the mechanization requirements and modifications required on existing 2D looms to commercialise the technology. In this regard the following observations are made. These observations are in addition to the existing features of the 2D loom.

1. Multiple warp beams with adjustable tensioning arrangement as compared with the standard one or two beams. This is required for distribution of warp yarns (with different path length) onto the different beams.
2. Electronic dobby with at least 24 heald frames. As per the weave architecture lifting patterns of the warp yarns changes compared to regular weaves. Hence the requirement of more number of heald frames.
3. Take-up at will would be required to stack the requisite number of weft layers as designed to obtain the 3D preform.

IV. SUMMARY

3D angle interlock structures with and without stuffer yarns were woven on a 2D weaving handloom. Both layer-to-layer and through-thickness structures were developed with different thicknesses and also with and without stuffer yarns. It has been observed that special requirement on the machine front calls for multiple warp beams and take-up at will options. These structures required pressure injected RTM process for conversion to composites. Overall improvement of all mechanical properties tested has been found in the case of structures with stuffer yarns, noticeable in the case of ILSS. It has been concluded that composites fabricated using 3D angle-interlock structures with stuffer yarns have improved overall properties and have bright commercial prospects for exploitation and use in composite structure.

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